INTERNATIONAL LINEAR COLLIDER

SLAC

ILC High Level RF

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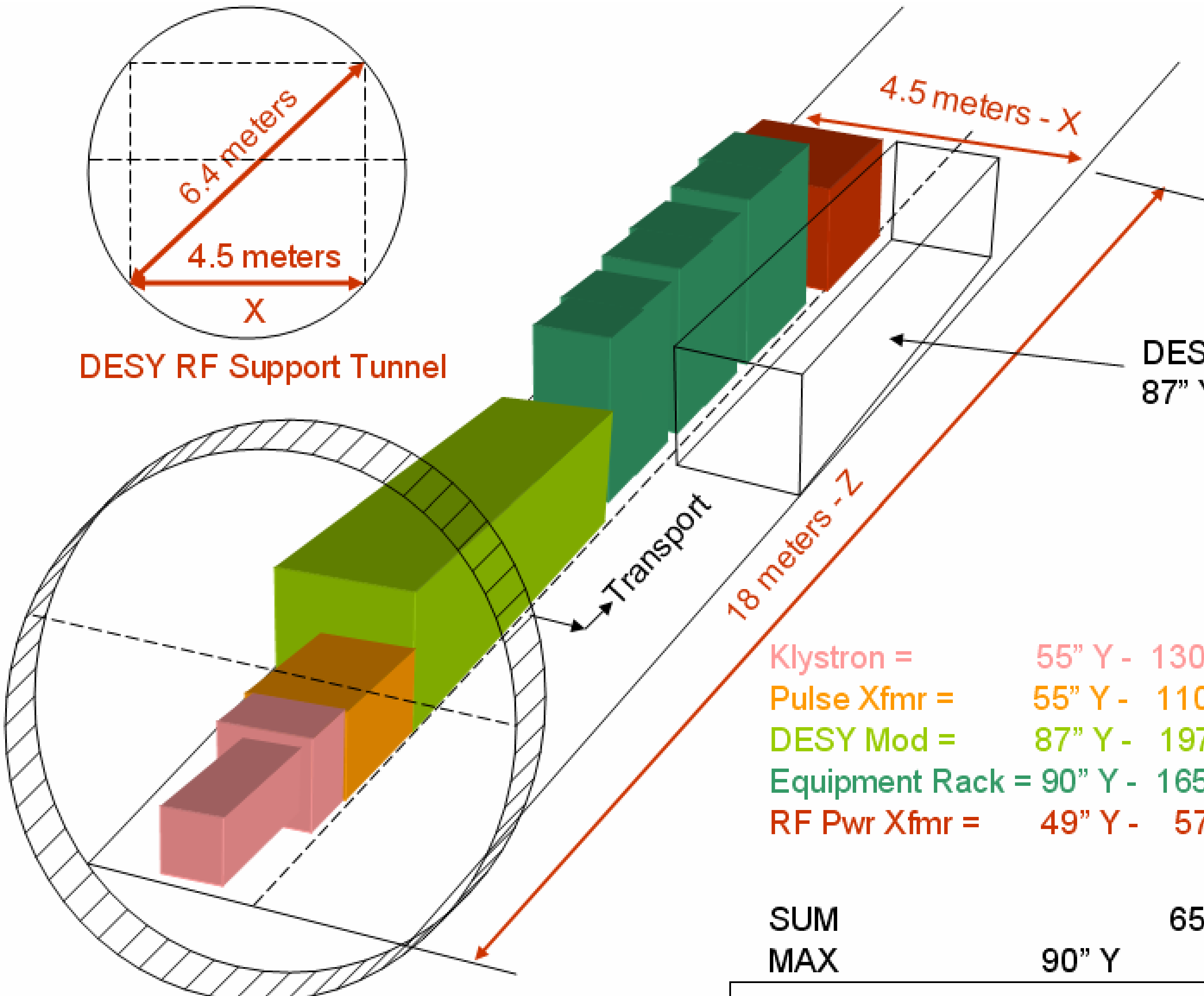
Rev. 1

HLRF Topology and Scope

- Baseline Conceptual Design (BCD) System includes Klystrons, Modulators and Power Distribution.
  - Klystron is 10 MW 1.3 GHz pulsed CW tube
  - Modulator is solid state 1:12 step-up transformer design with Bouncer pulse top flatness compensator
  - Distribution is coupler system from each 10MW klystron into 3 cryomodules of 8 cavities each, 24 cavities total, 36m long
  - Total RF units in both linacs is 328x2=656 w/ 5% overhead.
  - Assume Horizontal mounting (could be vertical depending on tunnel height)
  - Assume two tunnels with M-K in support tunnel with short cables (c.f. original TESLA proposal)

RF Support Tunnel Layout – BCD Model



		Oil Gal.	Wt.
Klystron =	55” Y - 130” Z - 48” X	?	?
Pulse Xfmr =	55” Y - 110” Z - 48” X	?	?
DESY Mod =	87” Y - 197” Z - 71” X	?	?
Equipment Rack =	90” Y - 165” Z - 30” X	dry	?
RF Pwr Xfmr =	49” Y - 57” Z - 68” X	?	?

SUM		659” Z	
MAX	90” Y		71” X

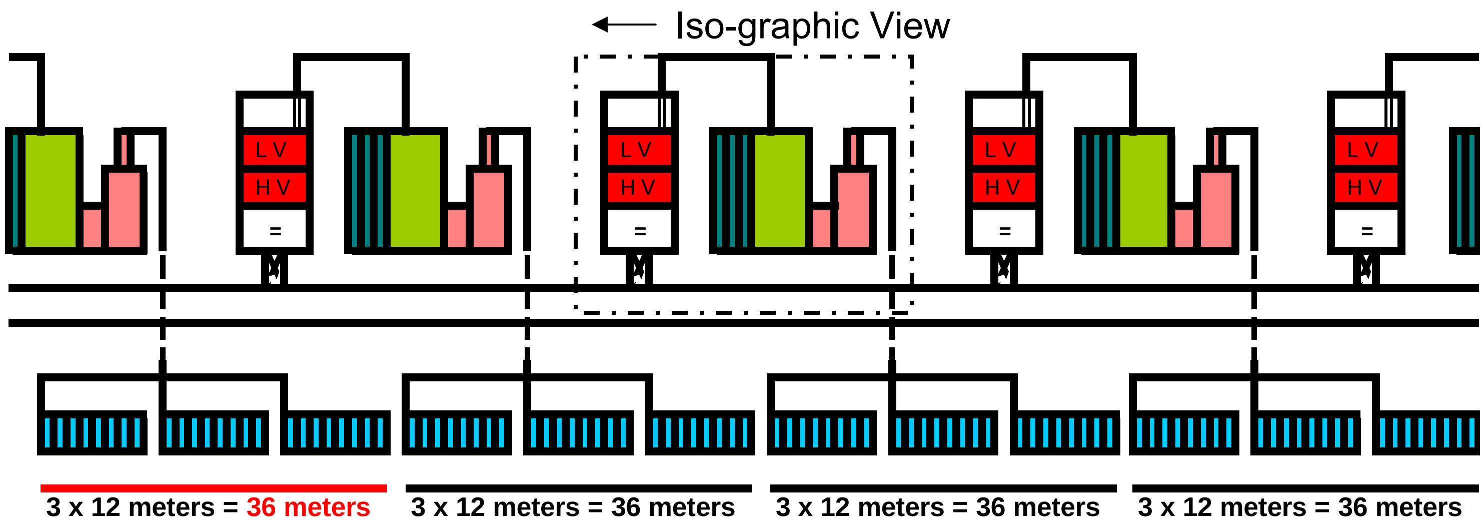
By C. Corvin, SLAC per data from S. Choroba, DESY

RF Support Tunnel Layout - BCD Model

DESY RF Support Tunnel

328 Disconnects (1 per)
328 RF Pwr Transformers
984 Control Racks (dbl)
328 DESY Modulators
328 10 MW Klystrons
328 Primary RF Switch
2 Primary Power Loops

984 8 Cavity Cryomodules (3 per cluster)



82 RF Power Unit — RF Power Unit = 144 meters

1 RF Power System — Total 250 GeV Linac RF Length: 82 x 144 meters = 11,808 meters

2 Cryo Refrigerators — Total 250 GeV Linac Cryo Refrigerator Length: 11,808 / 2 = 5,904 meters

24 Cryo Maint. Units — Total 250 GeV Linac Cryo Maintenance Unit Length: 11,808 / 24 = 492 meters

20.5 Cryo Maint. Units — Total 250 GeV Linac Cryo Maintenance Unit Length: 11,808 / 20.5 = 576 meters = 16 x 36 meters

RF Pwr Units per Cryo Maintnenace Unit — RF Power Units per Cryo Maintenance Units: 576 meters / 144 meters = 4

By C. Corvin, SLAC per data from S. Choroba, DESY

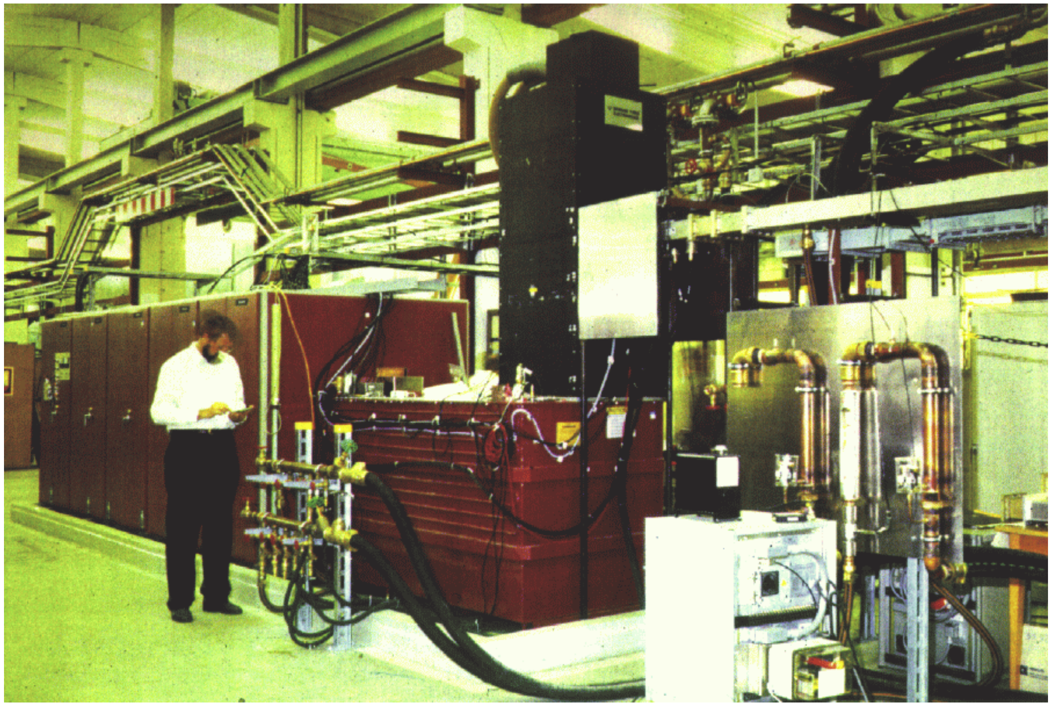
BCD Klystron Requirements

- Multibeam (MBK) 10MW 1.3 GHz tube, dual output windows
- Power output 10 MW at 1.3 Ghz
- Overhead for feedback: 10%
- Overhead for circulator, WG losses: 6%
- Available to 24 cavities = 84% = 8.4MW=350KW/cavity
- RF pulse length: 1.5 ms
- Cavity fill time: 0.5 ms
- Beam pulse length: 1.0 ms
- Repetition rate: 5 Hz Main Linac
- Number of Stations both linacs: 656
- Station overhead: 12 for both linacs (~2%)

Electrical Characteristics

- Peak Voltage: 120 kV Max
- Beam Current: 130A Max (for 7 Beams)
- Microperveance: 0.5 x 7 = 3.5 ($p=10^6 I/V^{3/2}$)
- RF Average Power: 75 kW @ 5Hz
- Efficiency: 65%
- Gain: 48dB
- Solenoid Power: 6kW
- No. cavities: 6
- Bandwidth: 8MHz *(Ref. C. Adolphsen)*

BCD Klystron & Modulator Assembly



Photos courtesy S. Choraba, DESY

INTERNATIONAL LINEAR COLLIDER

BCD Modulator Requirements

- TESLA Solid State switch with 1:12 step up transformer to Klystron, Bouncer pulse top flattener, Coaxial HV cables
- Output voltage: 120kV Maximum
- Output current: 140A maximum
- Pulse Duration: 1.5mS flat top, 1.52mS FWHM @ 5Hz
- Tr, Tf <200μSec
- Flat top tolerance: +/- 0.5%
- Output Power: 128kW Max @ 5Hz
- Efficiency: 85%
- Input Power: 150kW

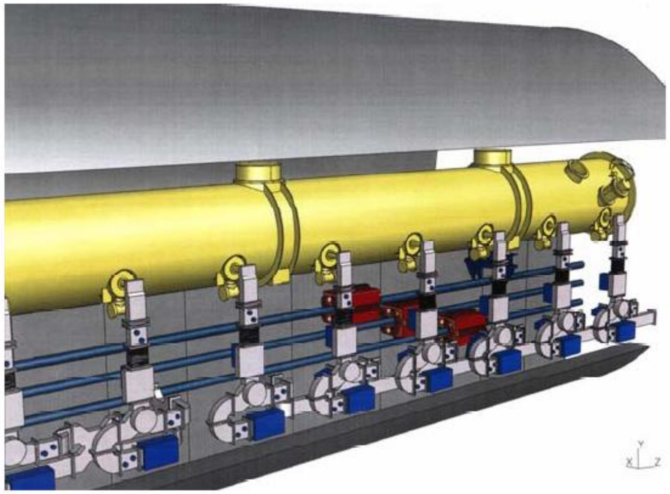
Charging Supply

- Output Power: 150KW Max
- Power line allowable distortion: D< 0.5% (<1MVA per RF station)
- Redundancy for reliability/availability (Original TESLA design for single tunnel was 1/N redundant modular supply)

Other M-K Requirements Noted

- Protection against arcs: Klystron, waveguide, cables by snubber, crowbar, fast switch-off charger.
- Klystron arc limit to 20J (actual depends on klystron arc mechanism and stored charge. Much larger numbers measured)
- Interlock protection system
- Intelligent diagnostics (mentioned in TDR and some recent papers)
- Fiber communication.

HLRF Distribution

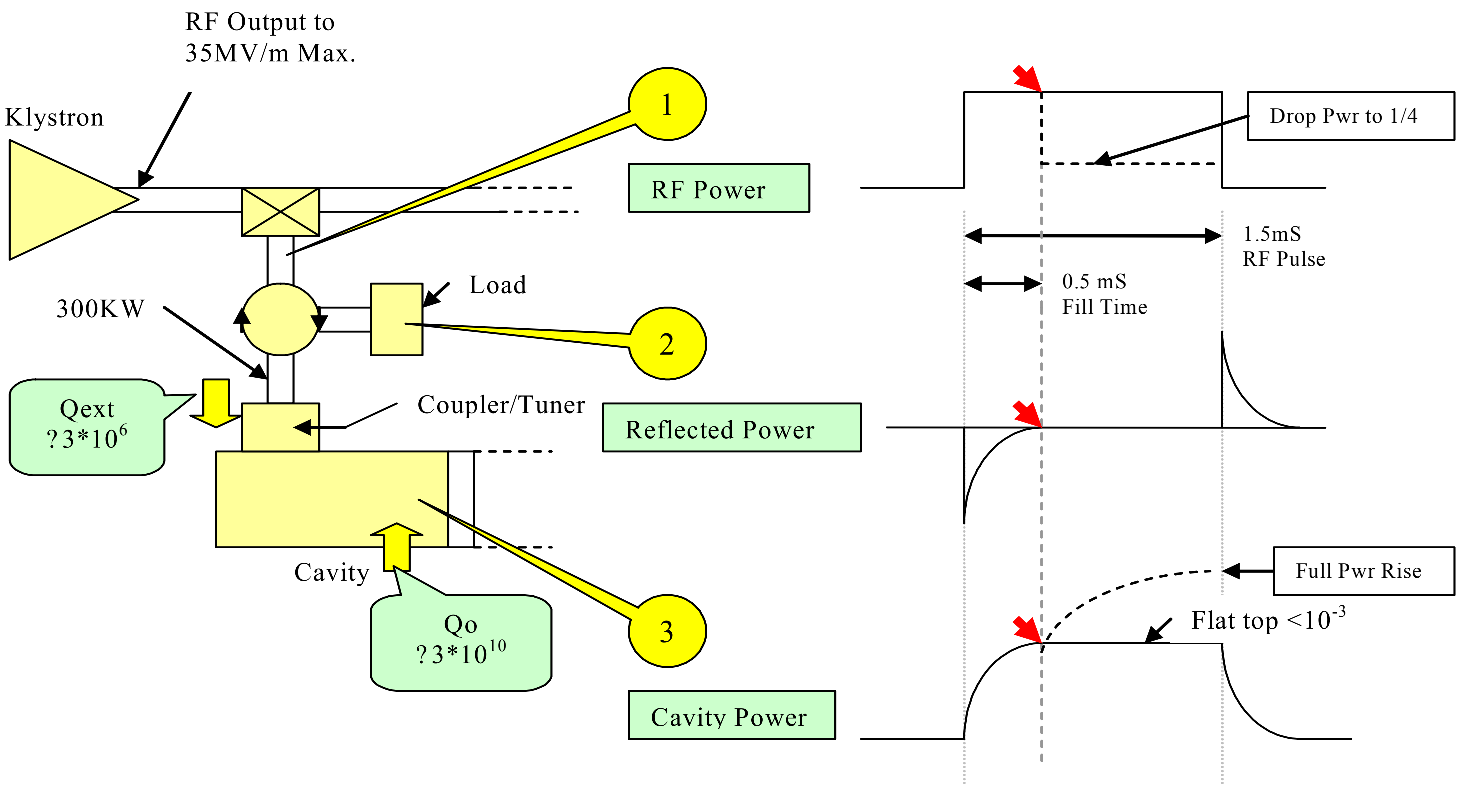


- *Ref. DESY ITRP Poster by V. Katalev, A. Eislage & E. Seesselberg, 2004.*

RF Power Distribution

- Power output/klystron= 10 MW at 1.3 Ghz
- Overhead for feedback: 10%
- Overhead for circulator, WG losses: 6%
- Available to 24 cavities = 8.4MW = 350 kW/cavity
- Required: Beam current I = 9.5mA avg; Vg=31.5MV/m avg; Vg*I = 299 kW/cavity => 16.7% headroom with average power available
- Distribution ideally equal power to every cavity by series hybrid couplers each with motor-driven 3-stub tuner to match *A*, *Ø*
- *Note: Distribution estimated to cost more than klystrons, modulators combined! (B. Rusnak, LLNL, Snowmass)*

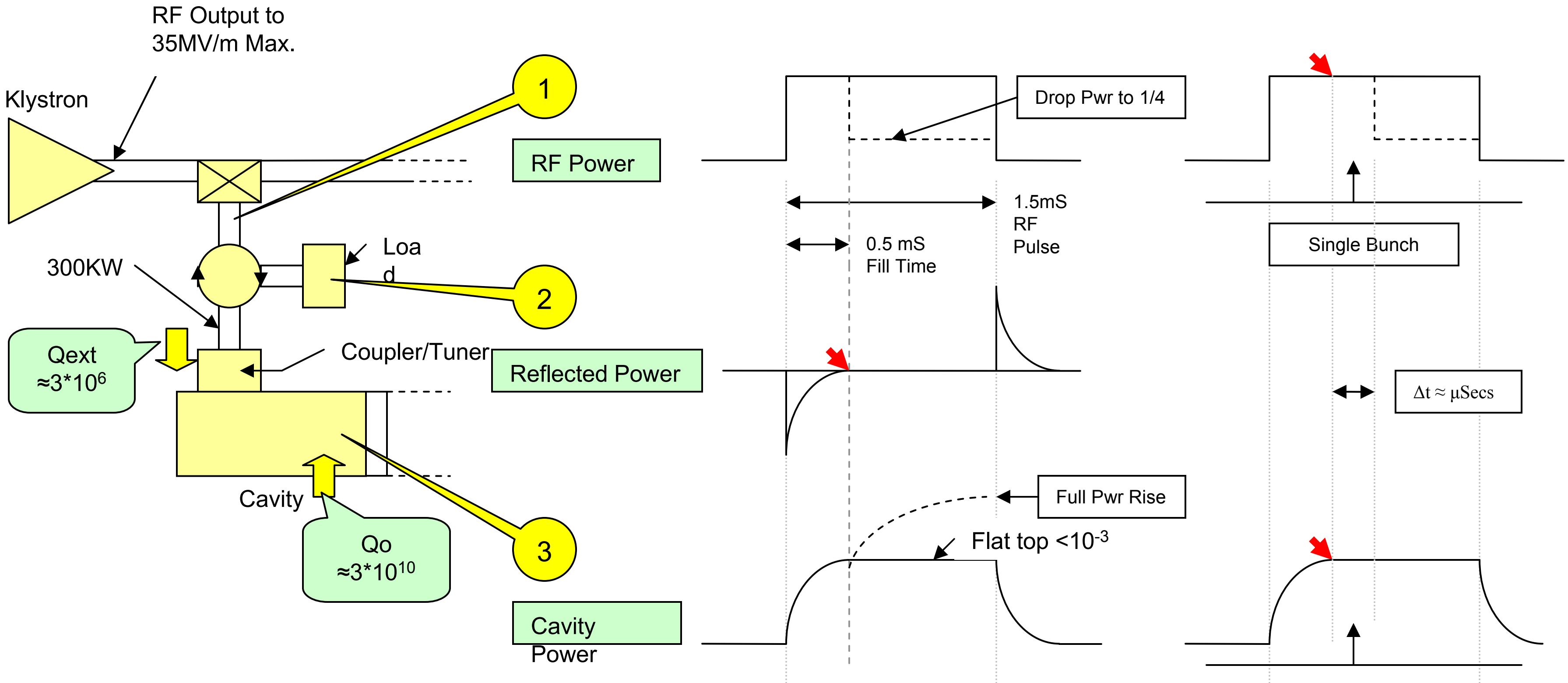
Power Control – No Beam



No Beam Operation

- ♦First 500µSec cavity fills to desired power of 31.5MV/m..
- ♦With no injection must drop applied power via LLRF to avoid exceeding max gradient of 35MV/m.
- ♦Reflected power goes to circulator load
- ♦Unused RF power goes into Klystron anode heating.

Power Control- Single Bunch



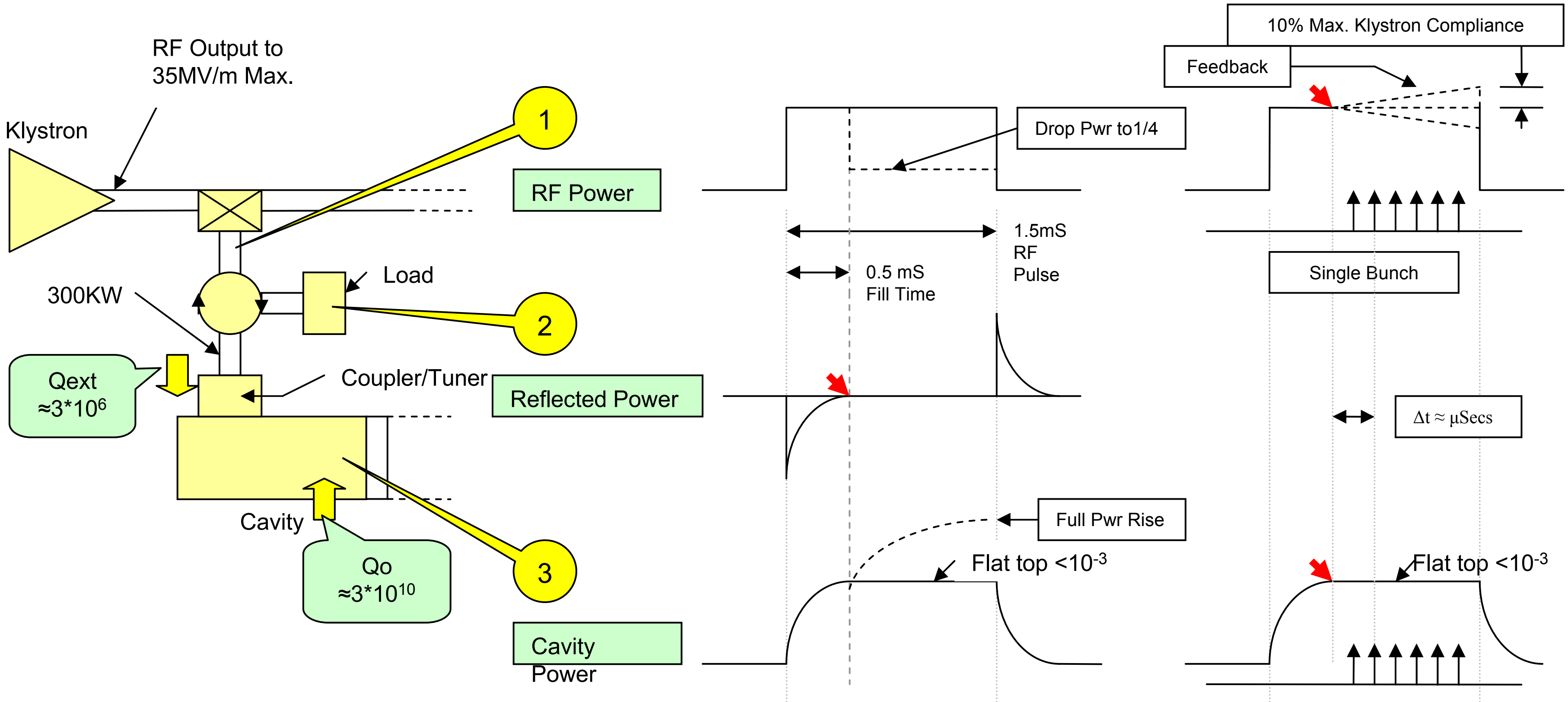
No Beam Operation

♦First 500μSec cavity fills to desired power of 31.5MV/m..
♦Immediately drop applied power via LLRF to avoid exceeding max gradient of 35MV/m.
♦Reflected power goes to circulator load
♦Unused RF power goes into Klystron anode heating.

Single Bunch Operation

♦First 500μSec cavity fills to desired power of 31.5MV/m..
♦Inject pulse immediately after reaching full cavity gradient of 31.5MV/m.
♦After pulse injected drop power to ~1/4 to maintain constant cavity power as before.

Power Control – Full Train



No Beam Operation

- ♦First 500μSec cavity fills to desired power of 31.5MV/m..
- ♦Immediately drop applied power via LLRF to avoid exceeding max gradient of 35MV/m.
- ♦Reflected power goes to circulator load
- ♦Unused RF power goes into Klystron anode heating.

Full Train Operation

- ♦First 500μSec cavity fills to desired power of 31.5MV/m..
- ♦Inject pulse train immediately after reaching full cavity gradient of 31.5MV/m.
- ♦Beam absorbs RF power & cavity RF flattens.
- ♦Feedback monitors RF power to maintain constant BEAM POWER to <0.3%.

Bandwidth - Klystron

- Klystron agility to respond to fast load changes by feedback depends on BW.
- BW depends on the loaded Q of its ~6 stacked cavities, BW=f_o/Q_L.
- -3dB BW not stated in specs but ~ 8MHz (Adolphsen)
- If 8MHz, gives Q_L = 1.3GHz/8MHz= 162
- Crudely speaking, Modulator noise sees an 8 MHz bandpass filter entering klystron (Charlie Brown View).

Bandwidth – Cavity (CBV)

- 24 Cavities comprise each klystron RF load.
- Cavity power level required constant to $<10^{-3}$, preferably at the single-cavity level, but most importantly over the full 24 connected loads *(Adolphsen).*
- Cavity power level response to fast changes of current or voltage depends on BW.
- Cavity BW is $f_o/Q_{ext} = 1.3\text{GHz}/3*10^6 = 433\text{Hz}$
- At f_o, Klystron load is 433Hz low pass filter
- Will attenuate >*433Hz* amplitude, phase noise.

Feedback Implications

- Klystron has only 10% compliance in RF power
  - Fast Feedback correction in + direction limited to +10% of normal average power out.
  - Some large fast random swings may not be correctable
- Feedback & Feedforward
  - Successful operation demonstrated at basic level for linac
  - Random swings easily correctable if not too fast
  - Systematic swings even if large, fast, correctable by feedforward that learns over several beam pulses
- What types of disturbances in RF power train cannot be corrected by feedback?
- What is effect of klystron, drive nonlinearities?

Single Cavity Control Issues

- Cavities will be tested at 35MV/m when received from manufacturing, but expect to average 31.5 MV/m when installed.
- Delivered power matched by tuners
- Feedback corrects:
  - Disturbances in RF power amplitude and phase (random <433 Hz, systematic)
  - Thermal changes in dimensions (slow, correctable by tuners)
  - Lorentz force detuning dimensional changes (fast, potentially into KHz range, mostly systematic, correctable by feed-forward)
- How to manage the following?
  - Very fast load disturbances due to glitches, arcs
  - Bunch-bunch current, energy jitter
  - Micro-quenches that recover after a few beam pulses, i.e. seconds

Exception Handling (Adolphsen)

- Major problem for LLRF algorithms
- Examples
  - Response to mini-quenches of single cavities resulting in loss of gradient and recovery time of seconds
  - Response to arcing cavities and waveguides
  - Detecting, correcting random bunch-bunch energy differences
  - Keeping machine tuned with rapid changes in beam conditions, power into klystrons and load conditions (no beam, single bunch, full beam)
  - Preventing machine aborts
  - Rapid Abort recovery
  - Working around failed piezos and tuner motors.

View from RDR Perspective

- All the difficult technical questions cannot be answered before RDR description & cost models are completed.
- Unresolved questions indicate areas of risk to high availability that will shape future R&D programs. Can be handled in RDR costs with risk assessment, contingency.
- The largest cost items will receive the most scrutiny and work to "get it right" in RDR
  - Example Machine costs (Barish): Civil 31%, Structures 18%, RF 12%, Controls 4%, Instruments 2%.
  - Example RF costs (Rusnak): Modulators 36%, Klystrons 10%, Distribution 54%. LLRF not included but presumably small c.f. Controls at 4%

Summary

- Amplitude, phase and detuning likely to be manageable to $<10^{-3}$, averaged over all 24 cavities, by LLRF system.
- Need learning and feed-forward to eliminate systematics.
- Power margin of 10% limits speed of correction.
- With limited power testing done to date we have no direct measure of many effects such as full pulse train loading, cavity management of all the parameters needed in correction (Adolphsen)
- LLRF system should be designed to be extremely intelligent and robust as called for in the TDR to and to easily grow new learning capabilities over time.

Acknowledgment

- Thanks to Chris Adolphsen for valuable tutorials and reference materials, and to many other ILC collaborators who developed most of the data cited.